Renewable and Sustainable Energy Reviews 13 (2009) 2430–2440

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review on fuel cell technologies and power electronic interface

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ARTICLE INFO

Article history:
Received 8 January 2009
Received in revised form 16 April 2009
Accepted 22 April 2009

Keywords:
Distributed generation
Renewable energy sources
Fuel cell systems
Power-conditioning units
dc/dc converters
dc/ac inverters

ABSTRACT

The issue of renewable energy is becoming significant due to increasing power demand, instability of the rising oil prices and environmental problems. Among the various renewable energy sources, fuel cell is gaining more popularity due to their higher efficiency, cleanliness and cost-effective supply of power demanded by the consumers. This paper presents a comprehensive review of different fuel cell technologies with their working principle, advantages, disadvantages and suitability of applications for residential/grid-connected system, transportation, industries and commercial applications. Development of mathematical model of fuel cell required for simulation study is discussed. This paper also focuses on the necessity of a suitable power-conditioning unit required to interface the fuel cell system with standalone/grid applications.

Contents

1. Introduction

Ever increasing energy consumption, rising public awareness for environmental protection and existing nature of fossil fuels, results much of the research work to focus on alternative/renewable energy sources. The small-scale generation systems such as wind turbine, photovoltaic, micro-turbines, fuel cells, etc. plays an important role to meet the consumers demand using the concepts of distributed generation. The term distribution generation means any small-scale generation is located near to the customers rather than central or remote locations. Survey [1] shows that at the end of year 2005 the total loss over the transmission, distribution and transformers in India is about 32.15%. The major benefits of distributed generation systems (DGs) are saving in losses over the long transmission and distribution lines, installation cost, local voltage regulation, and ability to add a

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doi:10.1016/j.rser.2009.04.004

Table 1
Comparison of different generation systems.

	Reciprocating engine: diesel	Turbine generator	Photo voltaics	Wind turbine	Fuel cells
Capacity Range	500 kW to 5 MW	500 kW to 25 MW	1 kW to 1 MW	10 kW to 1 MW	200 kW to 2 MW
Efficiency	35%	29–42%	6–19%	25%	40–60%
Capital Cost ($/kW)	200–350	450–870	6600	1000	1500–3000
O&M Cost ($/kW)	0.005–0.015	0.005–0.0065	0.001–0.004	0.01	0.0019–0.0153

small unit instead of a larger one during peak load conditions [2]. Among the different distributed generation more attraction is going on fuel cells because it has the potential capability of providing both heat and power.

Fuel cells are static energy conversion devices that convert the chemical reaction of fuels directly into electrical energy and produces water as its byproduct [3,4]. While, the conventional heat engines produces electricity from chemical energy with the use of intermediate mechanical energy conversion which results in reduced efficiency compared with fuel cells. The fuel cells combine the best features of engines and batteries; like an engine they can operate for long as fuel is available without any intermediate mechanical energy conversion and the characteristics of fuel cells are similar to a battery under load conditions [5]. Some of the special issues in distributed power generation to interface the fuel cells with grid connection and their relevant aspects to control the grid voltage and frequency to improve the quality of supply are also discussed [6,7].

Looking to the wide potential in fuel cell based distributed generation a detailed review based on basics of fuel cell technologies, *I–V* characteristics and power-conditioning unit required is needed. This paper presents a comparative study of different generation system based on their percentage efficiency, capital and maintenance cost. Based on the available literature a comparison of different fuel cell types is also presented [8–34]. A review of basic principle of working, classifications, advantages, disadvantages and suitability of applications are presented. Requirement of a suitable power-conditioning unit is an important aspect. An attempt is being made here to review the power-conditioning unit requirement based on single stage and multistage conversion [35–53].

Table 1 shows a comparison of different generation systems. It is observed that the efficiency of fuel cells is always higher as compared with conventional system and other distributed generation systems. While comparing the fuel cell with other distributed generation technologies, it offer more advantages like high energy conversion efficiency, zero emission, modularity, scalability, quick installation and gives good opportunities for cogeneration operations [40,54].

It is aimed that this paper may be very useful for upcoming researchers to understand the fuel cell technologies concept easily. The basic principles and chemical reactions involved in different fuel cells and recent developments are discussed in Section 2. Further importance of study on modeling of PEM fuel cells and comparison of different fuel cell models are discussed in Sections 3 and 4. The development in power electronic interface for fuel cell applications is discussed in Section 5.

2. Fuel cells technology

The basic principle of the fuel cell was discovered in the year 1838 by Swiss scientist Christian Friedrich Schönbein. In 1839 Sir William Grove developed the first fuel cell based on reversing the electrolysis of water by an accident [4]. In 1950 Francis Bacon at Cambridge University demonstrated the first 5 kW alkaline fuel cell. After the successful development of alkaline fuel cells, NASA needed a compact system to generate electricity for space shuttle applications. In 1970s, international fuel cells developed a 12 kW alkaline fuel cell for NASA's space shuttle orbiter to supply reliable power without the use of any backup powers like batteries. Beginning in the mid-1960s, the research work was focused on further development of various fuel cells for applications like stationary powers and transportations. Further the government agencies in the USA, Canada and Japan have significantly increased their funding for fuel cell in R&D [5]. But in many countries it was taken into account after 50 years, because of its major drawback of higher installation cost. After the development of power conversion devices much more researches are going on fuel cells to reduce its higher installation cost.

2.1. Principle of working

A fuel cell is an energy conversion device that converts the chemical energy of a reaction directly into electricity with byproduct of water and heat. The structure of a simplified fuel cell is shown in Fig. 1 [8]. The fuel cell consists of an electrolyte layer in contact with two electrodes on either side. The hydrogen fuel is fed continuously to anode electrode and the oxidant (or) oxygen from air is fed continuously to the cathode electrode. At the anode terminal the hydrogen fuel is decomposed into positive ions and negative ions. The intermediate electrolyte membrane permits only the positive ions to flow from anode to cathode side and acts as an insulator for electrons. These electrons want to recombine on the other side of the membrane for the system to become stable, for which the free electrons moved to the cathode side through an external electrical circuit. The recombination of the positive and negative ions with oxidant takes place at the cathode to form depleted oxidant (or) pure water. The chemical reactions involved in the anode and cathode and its over all reactions are given as

Anode reaction:

$$H_2 \Rightarrow 2H^+ + 2e^- \tag{1}$$

Cathode reaction:

$$1/2O_2 + 2H^+ + 2e^- \Rightarrow H_2O \tag{2}$$

Overall reaction:

$$H_2 + 1/2O_2 \Rightarrow H_2O \tag{3}$$

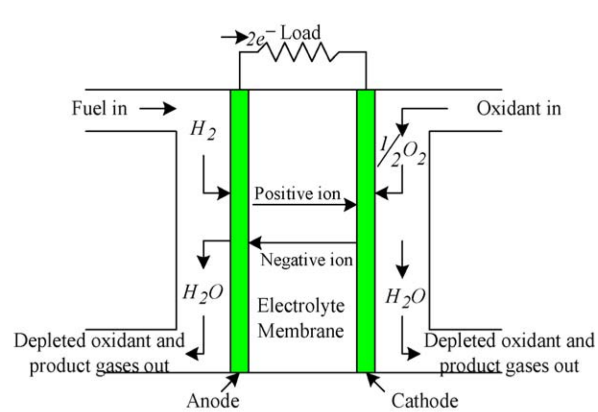

Fig. 1. Fuel cell operation diagram.

2.2. Classification of fuel cells

The fuel cells are classified according to the choice of electrolyte and fuel. Presently six major different types of fuel cells are available.

(i) Proton exchange membrane fuel cell (PEMFC):
  (a) Direct formic acid fuel cell (DFAFC);
  (b) Direct Ethanol Fuel Cell (DEFC).
(ii) Alkaline fuel cell (AFC):
  (a) Proton ceramic fuel cell (PCFC);
  (b) Direct borohydride fuel cell (DBFC).
(iii) Phosphoric acid fuel cell (PAFC)
(iv) Molten carbonate fuel cell (MCFC)
(v) Solid oxide fuel cell (SOFC)
(vi) Direct methanol fuel cell (DMFC)

They are further classified on the basis of operating temperature. The low operating temperature is in the range of (50–250) °C for PEMFC, AFC and PAFC, and high operating temperature in the range of (650–1000) °C like MCFC and SOFC. Based on review conducted [9–23] the main advantages, disadvantages and suitability of application of all fuel cells are briefly described.

2.2.1. Proton exchange membrane fuel cell (PEMFC)

The PEM fuel cell uses a solid polymer electrolyte (Teflon-like membrane) to exchange the ions between two porous electrodes, which is an excellent conductor of protons and an insulator for electrons. The operating temperature of the fuel cell is as low as around 100 °C. The chemical reactions are involved in anode and cathode sides and their overall reactions are given in Eqs. (1)–(3) [9].

The advantages of the PEM fuel cell are its higher power density and quick start up for automotive vehicles. The low operating temperature makes the technology competitive in transportation and commercial applications like laptop computers, bicycle, and mobile phones. The major drawbacks of the PEM fuel cell are its lower operating efficiency (40–45%) and use of high cost platinum catalyst. It is also intolerant to carbon monoxide. The PEM fuel cell-based power sources are also being developed for residential (3–7 kW) and building (50 kW) electricity and hot water applications. A 250 kW PEM power source is developed by Ballard Power Systems, Canada, for the distribution power generation [10]. Currently the development of 7 kW PEM is carried by plug power for residential applications. DFAFC and DEFC come under the subcategory of PEMFC discussed below.

2.2.1.1. Direct formic acid fuel cell (DFAFC). In DFAFC, the inlet fuel formic acid (HCOOH) consists of small organic molecules is directly fed to the anode electrode. The main advantage is formic acid does not crossover the polymer results the efficiency of the concentrations is higher (20–40%) compared to methanol (~6%) and the power density (17 mW/cm^2) is also very low. The DFAFC produces an open circuit voltage of 0.55 V at 60 °C operating temperature which is very low compared to theoretical value of 1.45 V given by Gibbs free energy [11]. It is also consider as safer fuel in case of leakage in fuel tank. But this technology is not considered formerly due to high electrochemical over voltage during loading conditions by using platinum as catalyst. In order to improve the performance, the Richard Masel's group at the University of Illinois uses palladium as catalyst [12].

2.2.1.2. Direct ethanol fuel cell (DEFC). For the further development of fuel cell types the DEFC comes under the sub category of PEM fuel cell due to its use of Nafion catalyst-like PEM fuel cell. The chemical reaction involved in DEFC is same as the PEM fuel cell, but it uses ethanol as input fuel instead of hydrogen. The ethanol fuel can be easily extracted from biomass through fermentation process from renewable energy sources such as sugar cane, wheat, corn or even straw. Here at the anode electrode with the mixture of water, the liquid ethanol (C_2H_5OH) is oxidized and generating CO_2, hydrogen ions and electrons. The reaction involved in cathode is same as PEM fuel cell and the generated voltage at its terminal is in the range of 0.5–0.9 V. World's first vehicle powered by a DEFC is presented by University of Applied Sciences at Shell's Eco-marathon in France [12].

2.2.2. Alkaline fuel cell (AFC)

The alkaline fuel cell is one of the earlier fuel cell system employed for NASA's space missions. Formerly it is also called as Bacon fuel cell after its British inventor. It operates at low temperature around 100 °C like PEM fuel cell and it has the capability to reach 60–70% of efficiency. It uses an aqueous solution of the potassium hydroxide (KOH) as an electrolyte. It transports negative charged ions from anode to cathode and releases water as its byproduct. This fuel cell gives quick start, one of its advantages. The major disadvantage is, it is very sensitive to CO_2 because it takes more time to react and consumes the alkaline in the electrolyte thereby reducing the concentration of hydroxide ion during chemical reactions [10,13]. It needs a separate system to remove the CO_2 from the air. The use of a corrosive electrolyte is also a disadvantage because it has shorter life span. Therefore it is not used for commercial applications. This type of fuel cells is used in transportations (i.e. in fleet vehicles and boats in Europe) and space shuttles.

2.2.2.1. Protonic ceramic fuel cell (PCFC). The protonic ceramic fuel cell (PCFC) is relatively new fuel cell type, which is developed basically with the ceramic electrolyte material. It can be operated at high temperatures of 750 °C and electrochemically oxidize gaseous molecules of the hydrocarbon fuels directly supplied to the anode without the need of additional reformer. Additionally it has solid electrolyte, so the membrane cannot dry out as with PEMFCs or liquid cannot leak out as with PAFCs [12]. The open circuit voltage produced by the PCFC is almost close to the theoretical value. But the major drawback of it is low current density that can be increased by reducing the electrolyte thickness, improved conductivity and optimized electrodes. The research also focused to increase the electrical efficiency of the PCFC in the range of 55–65% by pipeline natural gas and by increasing the high feed concentration of formic acid-like SOFC [14].

2.2.2.2. Direct borohydride fuel cell (DBFC). Sodium borohydride ($NaBH_4$) is potentially used as input fuel mixed with water to generate hydrogen by decomposing into $NaBO_2$ and $4H_2$. After releasing its hydrogen, gets oxidized at the cathode to produce $NaBO_2$ or borax. The DBFC fuel cell operated at low temperature of 70 °C. The major advantages are higher power density, no need of expensive platinum catalyst and high open circuit cell voltage (about 1.64 V). But the efficiency of the DBFC is low as 35%. Therefore research is focused on the development of increased efficiency with the aim of minimized borohydride hydrolysis reaction by using different catalysts like Au, Ni or Pd instead of platinum [15]. The cost of the sodium borohydride is too expensive for portable power applications. For that the researchers concentrating for recycling the $NaBO_2$ by electrochemical reaction to quantify sodium borohydride content in aqueous solution and by some other iodate back titration method to reduce its cost [16]. This DBFC technology is also still in the development stage compared to hydrogen powered fuel cells.

2.2.3. Phosphoric acid fuel cell (PAFC)

The phosphoric acid fuel cell operates at about 175–200 °C. This operating temperature is almost double as compared to that of PEM fuel cell. It utilizes a liquid phosphoric acid as an electrode. Unlike the PEM and AFC, it is very tolerant to impurities in the reformed hydrocarbon fuels. The chemical reaction involved in this fuel cell is same as PEM fuel cell where pure hydrogen is used as its input fuel [10]. The cogeneration is also possible due to its high operating temperature and the potential is also available for hot water supply as well as electricity depending on the heat and electricity load profile. The drawback of PAFC is same as PEM fuel cell, its cost also increases due to use of platinum as a catalyst. PAFC have been developed to the first stage of commercialization. The 100, 200 and 500 kW size plants are available for stationary and heat applications. A 1.3 MW system is already tested in Milan [13,17]. More over PAFC have been installed at 70 sites in Europe, USA and Japan.

2.2.4. Molten carbonate fuel cell (MCFC)

The molten carbonate fuel cell operates at high temperature, which is about 600–700 °C. It consists of two porous electrodes with good conductivity are in contact with a molten carbonate cell. Due to its internal reforming capability, it separates the hydrogen from carbon monoxide fuel and decomposition of hydrogen is taken through the water shift reaction to produce hydrogen, then the result of reaction is taken same as PEM fuel cell to produce electricity.

The major advantages of MCFC are higher efficiency as 50–60%, no need of metal catalyst and separate reformer due to its high operating temperature [10]. This cell is intolerant to sulfur and slow start up is one of its drawbacks. It is mainly used for medium and large power applications. A 1 MW plant is located in Kawagoe and 2 MW plant is also tested in Santa Clara, CA, for 4000 h [13].

2.2.5. Solid oxide fuel cell (SOFC)

The SOFC's are basically high temperature fuel cells. They use dense yttria stabilized zirconia, which is a solid ceramic material as its electrolyte. Here oxygen $O^{=}$ combines with hydrogen H^{+} to generate water and heat. The SOFC produce electricity at a high operating temperature of about 1000 °C. The main advantages of the SOFC is that they are operated at high efficiency of 50–60% and a separate reformer is not required to extract hydrogen from the fuel due to its internal reforming capability. Waste heat can be recycled to make additional electricity by cogeneration operation [10,18]. The slow start up, high cost and intolerant to sulfur content of the fuel cell are some of its drawbacks. It is not suitable for larger fluctuations in load demand. Therefore, the SOFC is mainly used for medium and large power applications. In 1997 a Ceramic Fuel Cells Limited Company was demonstrated a 5 kW laboratory prototype fuel cell system. Yakabe et al. [19] developed a 3 kW SOFC at Tokyo gas Co. Ltd. and they are also analyzed the key factors to improve the performance of SOFC in the micro-grid system. At present the research is going to build a 250 kW commercial stack model.

2.2.6. Direct methanol fuel cell (DMFC)

The DMFC technology is relatively new when compared to rest of the fuel cells. Like PEM fuel cell, the DMFC uses polymer electrolyte. But DMFC uses liquid methanol or alcohol as fuel instead of reformed hydrogen fuel. During chemical reactions, the anode draws hydrogen by dissolving liquid methanol (CH_3OH) in water in order to eliminate the need of external reformer. At the cathode, the recombination of the positive ions and negative ions takes place, which are supplied from anode through external circuit and it is combined with oxidized air to produces water as a byproduct.

Normally a single DMFC can supply only 0.3–0.5 V under loaded conditions. It is mainly used to replace the batteries for cameras, notebook computers and other portable electronic applications in the range of 1 W to 1 kW capacity. The one of the main advantages is that the anode catalyst itself draws the hydrogen from the methanol and reduces the overall cost due to the absence of reformer. Its characteristics are similar to the PEM fuel cell, however their performance is limited by two important factors like, crossover of methanol from anode to cathode lowers the system efficiency and the slow kinetics of the electrochemical oxidation of methanol at the anode [20].

2.3. Recent development in fuel cells

The optimal selection of size of the fuel cell is important to locate the fuel cell in distributed system to meet the peak load demands for different applications of utilities [21]. The various intermediate ranges of different fuel cells available in markets from 0.5 kW to 2 MW are given in this classical paper [10]. Particularly the research is focusing on PEM, MCFC and SOFC fuel cells, to reduce the cost of the fuel stacks and to increase their life span more than 40,000 h. At present a 7 kW capacity PEMFC development is carried out by plug power for residential applications and 250 kW capacity is under tested condition by Ballard power generation system. The Department of Energy (DOE) and Fuel Cell Energy, Inc. have researched MCFCs heavily for stationary power applications. A 1.2 MW system is largest distributed generation power plant located at Santa Clara, CA and for the commercialization purpose the development of 250, 300 and 400 kW capacity MCFC for cogeneration is researched in various countries such as Europe, Holland, Italy, Germany and Spain [5–10,13]. The SOFC has like wise achieved success in stationary power applications. Siemens Westinghouse has developed and tested a 250 kW hybrid system that has achieved efficiency of 52% and the efforts are also going on to develop the SOFCs in different ratings as 1 and 25 kW. They are also developing a high efficiency 5 kW SOFC-GT system to reduce its high installation cost. More over further research is focusing on PEMFC and PAFC systems for the combined heat and power generation [13,17–19]. The research is also focusing on development of 100 kW to 1 MW DMFC and other fuel cell types such as DFAFC, DEFC, PCFC and DBFC for commercial applications [11–16,20].

3. *I–V* characteristics of fuel cells

The fuel cell voltage is usually very small, around 1.2 V. Due to their low output voltage it becomes necessary to stack many cells that need to be connected in cascaded series and parallel form to increase its power capacity. A typical fuel cell polarization characteristic with electrical voltage against current density is shown in Fig. 2 [22]. It can be seen that a linear region exists because as the current density increases the voltage drops due to its ohmic nature. This region is called ohmic polarization, it is mainly due to internal resistance offered by various components. At low current level, the ohmic loss becomes less significant; the increase in output voltage is mainly due to activity of the chemical reactions (time taken for warm up period). So this region is also called active polarization. At very high current density the voltage fall down significantly because of the reduction of gas exchange efficiency, it is mainly due to over flooding of waters in catalyst and this region is also called concentration polarization.

The performance of the fuel cell is improved by thermodynamics and electrical efficiency of the system. The thermodynamic efficiency depends upon the fuel processing, water management and temperature control of the system. But the electrical efficiency depends on the various losses over the fuel cells like ohmic loss, activation loss and concentration loss. In reality, the fuel cells differ in terms of characteristics, material used in construction and their

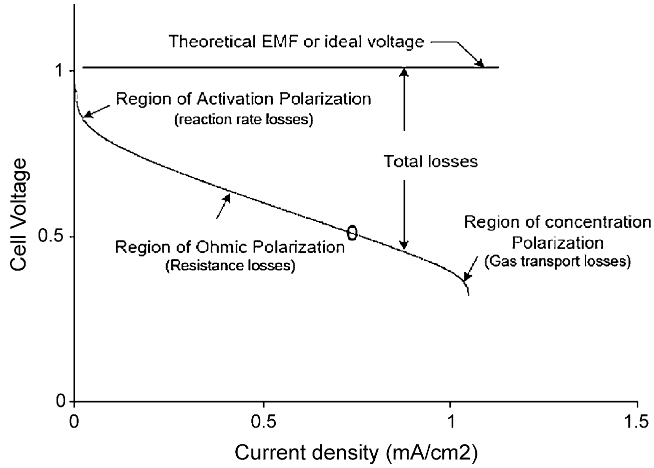

Fig. 2. Typical fuel cell polarization curve.

suitability of applications. This includes military, space, portable devices, residential, stationary and transportation applications [5,13].

3.1. Comparison of different fuel cell models

From the above discussion it is clear that development of an accurate of fuel cell model is very important. Several PEM fuel cell models are reported in the literature [23–29] based on the thermodynamic and electrochemical equations. In most of the cases the dynamic behavior of the fuel cell stacks is analyzed for constant hydrogen pressure operation only for simplicity. The effect of changes in inlet fuel pressures and operating temperatures of PEM fuel cell models are also addressed [23]. It has been observed that the fuel cell can be operated dramatically within the linear region by changing the internal resistance offered by the fuel cell stack with different loading conditions under different hydrogen pressure operations. del Real et al. [27] proposed a semiemperical formulation of fuel cell model based on theoretical and experimental results. The main objective for the design of fuel cell model is to overcome the problem of flooding due to sudden increase in load and to reduce the warm up period of the system. The electrochemical reaction involved in this model is given by the equations:

$$V_{fc} = V_o - V_{act} - V_{ohm} - V_{con} \tag{4}$$

$$V_o = \underbrace{x_1}_{v_o} + \underbrace{x_2(T_{st} - T_{st}^o)}_{\Delta V_{fc}/\Delta T_{st}} + \underbrace{x_3(0.5\ln(PO_{2,ca}) + \ln(PH_2))}_{\Delta V_{fc}/\Delta P} \tag{5}$$

$$V_{act} = -x_4(1 - \exp(-j/x_5)) \tag{6}$$

$$V_{ohm} = -x_6 j \tag{7}$$

$$V_{con} = -x_7 j^{(1+x_8)} \tag{8}$$

where V_{fc} is the fuel cell terminal voltage, V_o is the open circuit voltage, V_{act} is the activation loss, V_{ohm} is the ohmic loss and V_{con} is the concentrations loss, T_{st} is the stack temperature, PO_2 is the partial oxygen pressure, PH_2 is the partial hydrogen pressure and x_1 to x_8 are electrochemical parameter constants.

Tirnovan et al. [28] presented a parametric model based on the combinations of empirical and mathematical modeling techniques. They have tested the performance of the model based on different values of operating temperatures and inlet pressures. More over they also adopted semi empirical approach for their fuel cell modeling. The potential characteristic of the voltage versus current density based on Nernst equation for a single cell is given by equations:

$$V(j) = V_{rev} - V_{ohmic} - V_{act} - V_{con} \tag{9}$$

$$V_{rev} = 1.229 - 0.85 \times 10^{-3}(T - T_{ref}) + 4.31 \times 10^{-5} T\left[\ln(PH_2) + \frac{1}{2}\ln(PO_2)\right] \tag{10}$$

$$V_{ohmic} = i(R_m + R_c) \tag{11}$$

$$R_m = \frac{\rho_m l}{A} \tag{12}$$

$$\rho_m = \frac{181.6[1 + 0.003j + 0.062(T/303)^2 j^2]}{(\lambda - 0.634 - 3j)e^{4.18(1-(303/T))}} \tag{13}$$

$$V_{act} = -[\xi_1 + \xi_2 T + \xi_3 T\ln(CO_2) + \xi_4 T\ln(j)] \tag{14}$$

$$V_{con} = -B\ln\left(1 - \frac{j}{j_{max}}\right) \tag{15}$$

where V_{rev} is the open circuit reversible voltage, i is the stack current, j is the current density, R_m is the equivalent membrane resistance, R_c is the constant resistance, ρ_m is the membrane specific resistivity, T is the operating temperature, ξ_1 to ξ_4 are parametric coefficients and B is the constant coefficient.

Based on Eqs. (4)–(15) fuel cell models are developed in Matlab/Simulink environment for the operating temperature of 70 °C. Figs. 3 and 5 show the dynamic model of Ballard 1.2 kW and BCS 500 W PEM fuel cell models developed in Matlab/Simulink. The simulated I–V characteristics of above two models such as Nexa™ 1.2 kW and BCS 500 W fuel cell stack is shown in Figs. 4 and 6, respectively. Fig. 7 shows the experimentally measured characteristics of 1.2 kW Nexa™ PEM fuel cell [42], which is almost similar to the simulated characteristics curve shown in Fig. 4. Based on this the polarization curve can be linearized using formula $V_{fc} = E_{fc} - R_{fc} i_{fc}$ for further investigations. Where V_{fc} is the linearized output voltage, E_{fc} is the open circuit voltage, R_{fc} is the linearized resistance and i_{fc} is the fuel cell current.

It is observed that the fuel cell can be operated in between the lower and upper current limits. Among the different power ratings of PEM fuel cells such as Nexa™ 1.2 kW, SR 500 kW and BCS 300 W, the experiment work is carried out to analyze the effect of warm up period of fuel cell stacks [29]. It is observed that the Nexa™ PEM 1.2 kW model gives best performance with the start-up time of 2 min, compared with other models for higher power density.

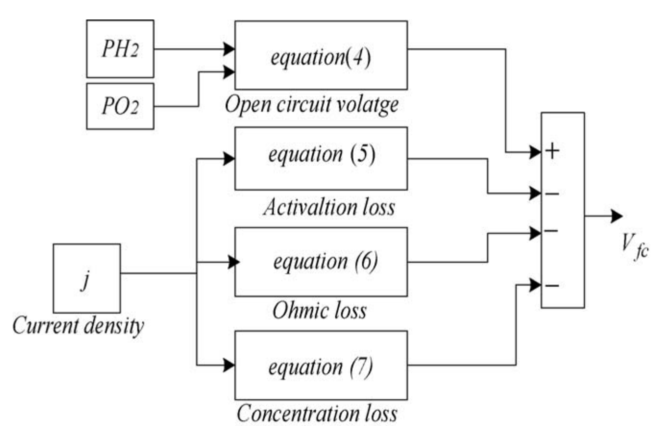

Fig. 3. Dynamic model of 1.2 kW Ballard PEM fuel cell in Matlab/Simulink.

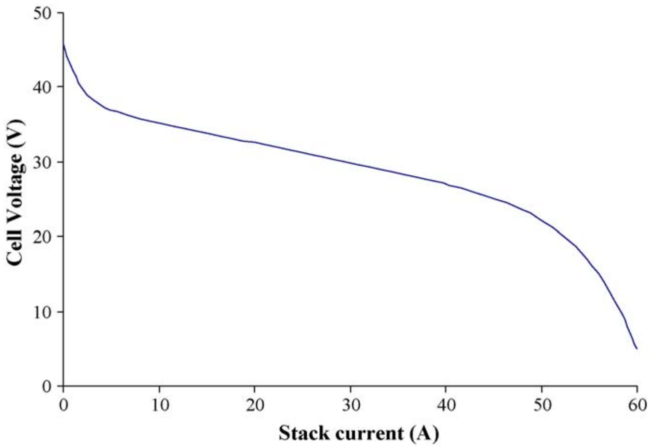

Fig. 4. Polarization characteristic curve (del Real et al. [27] model).

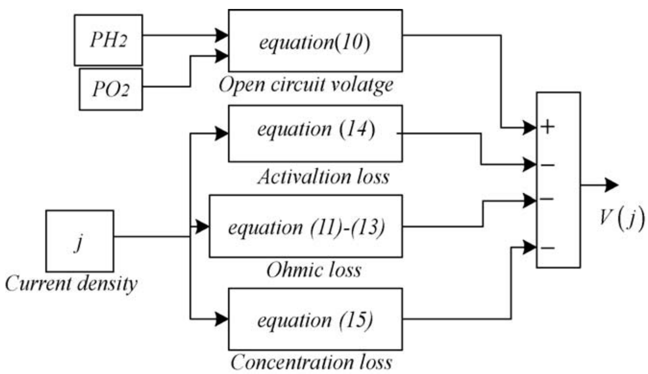

Fig. 5. Dynamic model of BCS 500 W PEM fuel cell in Matlab/Simulink.

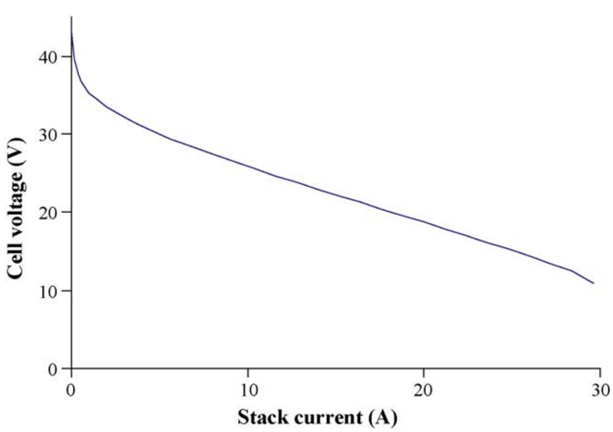

Fig. 6. Polarization characteristic curve (Tirnovan [28] et al. model).

4. Comparison of different fuel cells

Table 2 shows a comparison of major six fuel cells based on their inlet fuels, electrolyte material, cost, advantages, disadvantages and their suitability of applications. From the table it is clear that the PEM fuel cell is more suitable for residential and commercial applications due to the low working temperature (50–100 °C) and fast start up, but for the medium and large power applications the best choice is MCFC and SOFC. The SOFCs operate at the highest temperature among the all fuel cells that provide very high efficiency, internal reforming, fuel flexibility and high quality byproduct heat for cogeneration operation. It results in the efficiency of the system increased as high as 80% with combined

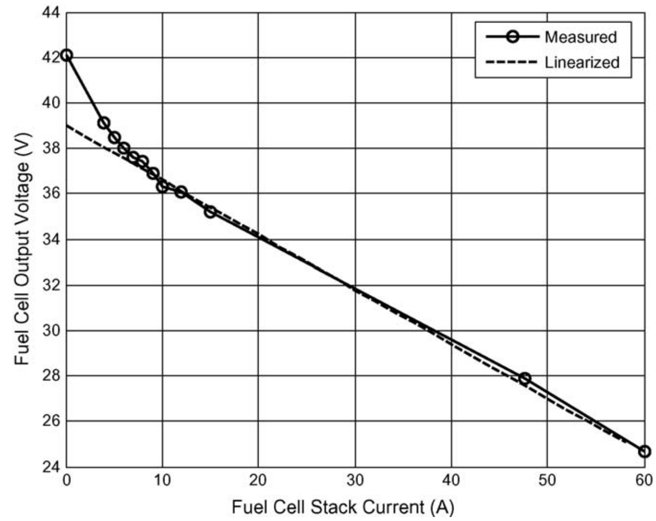

Fig. 7. Experimentally measured output characteristics of the Nexa^{TM}.

cogeneration operations and low emission of green house gases. But its high initial cost is the major drawback.

Therefore further research is going on these fuel cells to reduce the operating temperature and to reduce its higher installation cost. These capabilities have made SOFC an attractive emerging technology for stationary power generation in the 2 kW to several MW capacity ranges. The AFC is used for some special space programs, and the PAFC is also used for transportations and commercial applications. At present more than 2500 fuel cells are installed in all over the world for stationary applications like hospitals, hotels, schools, telecommunication offices and utility power plants. More over for portable applications like mobile phones, laptops, etc. The mobile phone can be operated up to 30 days without recharging and laptop up to 20 h that shows that the fuel cell can deliver longer power than the batteries [9–10,13,17–34].

5. Power-conditioning units (PCUs)

Looking to the drooping characteristics of fuel cell the development of power-conditioning units (PCUs) plays an important role to interface the fuel cell system with standalone/grid-connected system. The available fuel cell in the market is only in the range of 25–50 V due to its higher production cost. The generated fuel cell voltage is converted into directly ac supply by using single stage dc/ac inverter topologies or by a combination of a dc/dc converter in series with dc/ac inverter forming multistage conversion as shown in Fig. 8 [35].

The selection of power-conditioning unit is based on some significant factors like lower cost, higher efficiency, electrical isolation, ripple free and reliable operation. The efficiency of the power-conditioning unit depends upon the conduction and switching losses. The conduction losses can be effectively reduced by reducing the usage of components and their operating ranges. The switching losses can be reduced by soft switching techniques either by zero voltage crossing (ZVS) or zero current crossing (ZCS) techniques. The major advantages of soft switching technique over hard switching conditions are to reduce the losses over the device by about 20–30% [36]. In order to reduce the cost and to increase their reliability the selection of topology must have reduced component count. More over an electrical isolation is required to protect the fuel cell stacks under overload conditions. Table 3 shows a comparison between single stage and multistage energy conversion schemes.

Table 2
Comparison of different fuel cells.

Parameters	Fuel cell types					
	PEMFC	AFC	PAFC	MCFC	SOFC	DMFC
Electrolyte	Solid polymer membrane (Nafion)	Liquid solution of KOH	Phosphoric acid (H_3PO_4)	Lithium and potassium carbonate (LiAlO2)	Stabilized solid oxide electrolyte (Y_2O_3, ZrO_2)	Solid polymer membrane
Operating temperature (°C)	50–100	50–200	~200	~650	800–1000	60–200
Anode reaction	$H_2 \rightarrow 2H^+ + 2e^-$	$H_2 + 2(OH^-) \rightarrow 2H_2O + 2e^-$	$H_2 \rightarrow 2H^+ + 2e^-$	$H_2O + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$	$H_2 + O^2 \rightarrow H_2O + 2e^-$	$CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6H^-$
Cathode reaction	$1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O$	$1/2O_2 + H_2O + 2e^- \rightarrow 2(OH)^-$	$1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O$	$1/2O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$	$1/2O_2 + 2e^- \rightarrow O^{2-}$	$3O_2 + 12H^+ + 12H^- \rightarrow 6H_2O$
Charge carrier	H^+	OH^-	H^+	$CO_3^=$	$O^=$	H^+
Fuel	Pure H_2	Pure H_2	Pure H_2	H_2, CO, CH_4, other hydrocarbons	H_2, CO, CH_4, other hydrocarbons	CH_3OH
Oxidant	O_2 in air	O_2 in air	O_2 in air	O_2 in air	O_2 in air	O_2 in air
Efficiency	40–50%	~50%	40%	>50%	>50%	40%
Cogeneration	–	–	Yes	Yes	Yes	No
Reformer is required	Yes	Yes	Yes	–	–	–
Cell Voltage	1.1	1.0	1.1	0.7–1.0	0.8–1.0	0.2–0.4
Power density (kW/m^3)	3.8–6.5	~1	0.8–1.9	1.5–2.6	0.1–1.5	~0.6
Installation Cost (US $/kW)	<1500	~1800	2100	~2000–3000	3000	–
Capacity	30 W, 1 kW, 2 kW, 5 kW, 7 kW, 250 kW	10–100 kW	100 kW, 200 kW, 1.3 MW	155 kW, 200 kW, 250 kW 1 MW, 2 MW	1 kW, 25 kW, 5 kW, 100 kW, 250 kW, 1.7 MW	1 W to 1 kW, 100 kW to 1 MW (Research)
Applications	Residential; UPS; emergency services such as hospitals and banking; industry; transportation; commercial	Transportation; space shuttles; portable power	Transportation; commercial cogeneration; portable power	Transportations (e.g. marine-ships; naval vessels; rail); industries; utility power plants	Residential; utility power plants; commercial cogeneration; portable power.	It is used to replace batteries in mobiles; computers and other portable devices
Advantages	High power density; quick start up; solid non-corrosive electrolyte	High power density; quick start up	Produce high grade waste heat; stable electrolyte characteristics	High efficiency; no metal catalysts needed	Solid electrolyte; high efficiency; generate high grade waste heat	Reduced cost due to absence of fuel reformer
Drawbacks	Expensive platinum catalyst; sensitive to fuel impurities (CO, H_2S)	Expensive platinum catalyst; sensitive to fuel impurities (CO, CO_2, CH_4, H_2S)	Corrosive liquid electrolyte; sensitive to fuel impurities (CO, H_2S)	High cost; corrosive liquid electrolyte; slow start up; intolerance to sulfur	High cost; slow start up; intolerance to sulfur	Lower efficiency and power density

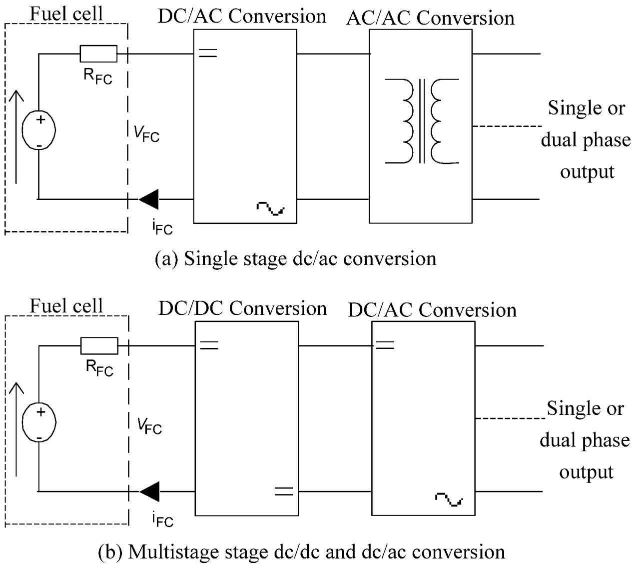

Fig. 8. Schematics of fuel cell power electronic-conditioning systems.

Table 3
Comparison of single stage and multistage power-conditioning units.

Single stage	Multistage
Converts directly dc into AC by dc/ac inverter	It needs a boosting dc/dc converter in front of dc/ac inverter
Component count is low	Component count is high
Switching loss is less	Switching loss is high
Requires high cost low frequency transformer	Requires low cost high frequency transformer
Low frequency ripples	High frequency ripples
High passive components	Low passive components
Efficiency is high	Efficiency is slightly lower than dc/ac inverters (due to more components)
Suitable for medium power applications	Suitable for both medium and high power applications

With the ideologies of fuel cell requirements and operations, several dc/dc converters and dc/ac inverter topologies are researched [35–51]. In dc/dc converters the efficiency of the conventional boost converter is always greater than the other converter topologies like push pull, half bridge, full bridge, etc., because it has reduced component counts and simplicity in control. But for the protection point of view electrical isolation is not possible in boost converter as shown in Fig. 9. However for isolation and high boost ratio, push pull, half bridge and full bride can be considered as candidate topologies [37]. Fig. 10 shows a push pull converter is used to reduce the conduction loss in switches by operating only one switch at any time to interface the fuel cell voltage to dc bus. But the major problem is the transformer saturation which results in converter failure because the two half portions of the center tap transformer windings cannot be equal or symmetrically wound. Therefore it is suitable for low and medium power applications only [38]. Though the half bride converter as shown in Fig. 11 is suitable for high power applications, it requires large value of secondary/primary transformation ratio to deliver the desired output voltage or it requires large value of dc link capacitors to eliminate the transformer saturation that increases cost of the converter [36]. The full bridge converter as shown in Fig. 12 is suitable for high power applications compared to half bridge. Though it has more components, it has an advantage of reduced device current ratings, transformer turns ratio and the voltage and current stresses are small compared with other topologies [40,41]. Table 4 shows the comparison of different dc/dc converters based on their types, electrical isolation, voltage stress, operating efficiency (η) and their advantages and disadvantages.

Development of dc/ac inverters topologies are also studied based on their relative characteristics under operating conditions.

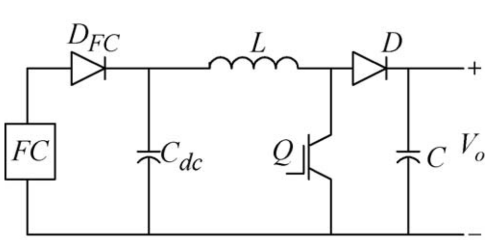

Fig. 9. Non-isolated dc/dc boost converter.

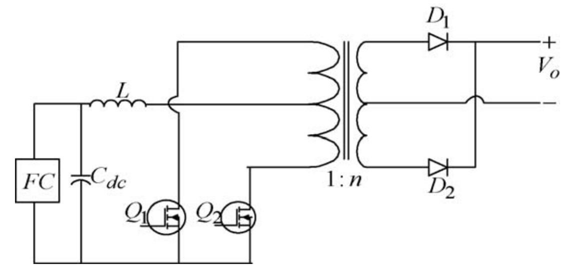

Fig. 10. Push pull converter.

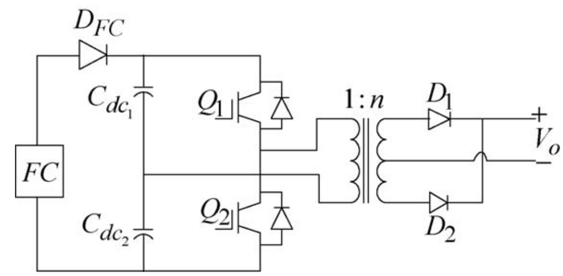

Fig. 11. Isolated half bridge dc/dc converter.

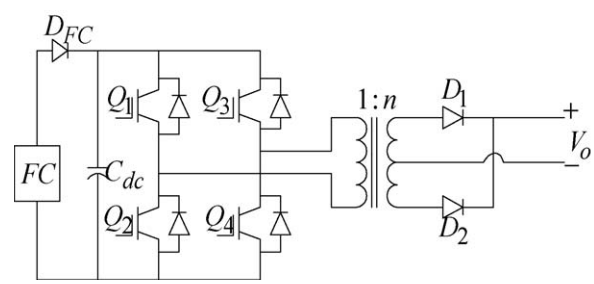

Fig. 12. Isolated full bridge dc/dc converter.

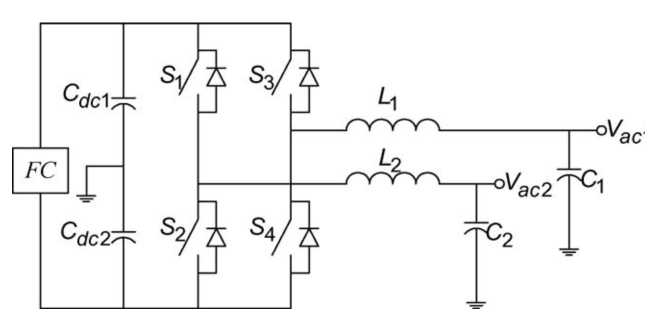

Fig. 13. Single bus inverter with two paralleled half bride topology.

Table 4
Comparison of different dc/dc converters.

Topologies	Electrical isolation	Voltage stress	η	Advantages	Disadvantages
Boost	No	Less	98%	Simple design and control; minimum component count	Low power applications
Push pull	Yes	Less	92%	Medium power applications; not more than one switch in series conducts at any instant of time; the voltage drop across more than one switch in series would results in a significant reduction in energy losses	Center tap saturation problem at high power; high transformer leakage inductance
Half bridge	Yes	Less	92–94%	The input capacitors are act as dc blocking capacitors; the transformer leakage inductance energy does not present a problem to the switches	Requires twice current rating of switches compared to full bridge; large capacitance is required
Full bridge	Yes	Less	95%	Soft switching possible	–
Voltage doubler	Yes	Less	–	Soft switching possible; current ripples is low	High cost; complex control
Current fed	Yes	High	94%	High conversion ratio (contains voltage doubler); minimization of conduction loss; lower transformer turns ratio; simplicity of construction	It suffers from severe voltage overshoots at turn off due to storage energy in the leakage inductor of the transformer; large inductor is required
Series resonant H bridge	Yes	–	–	It is inherited short circuit protection (snubber circuit); high boost capabilities	–
High step up	No	–	~96%	Coupled inductor prevents voltage drifts at the output, it gives larger gain	It needs a snubber circuit has been added to provide protection to the circuit components; component count is two times higher than conventional dc/dc converters
Three-phase transformer isolated (V6 converter)	Yes	–	95–97%	Low leakage reactance, It reduces high frequency current ripples; modular; reduced filter size	Highly complex

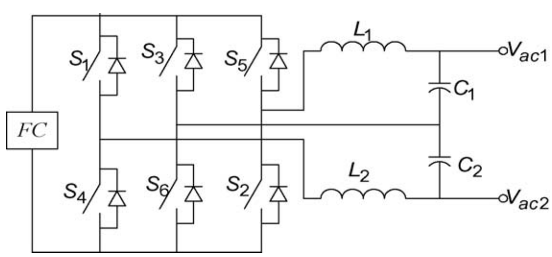

Fig. 14. Dual bus inverter with two split half bridge topology.

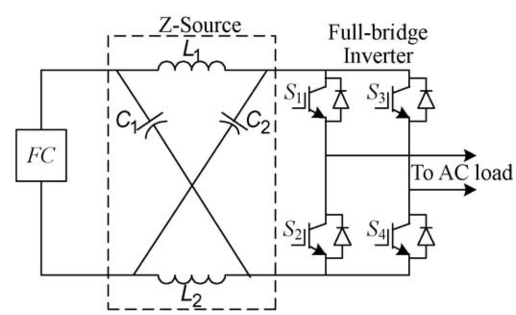

Fig. 16. Z source inverter.

From this paper [38,42], it is clear that for single phase loads single phase 3 wire inverter shown in Fig. 13 is the best choice compared to single bus inverter with two paralleled half bridge inverter and dual bus inverter with two split half bridge topologies, because it satisfies the ultimate basic requirements of reduced components, simple design and control. From the cost point of view it is clear that a single bus inverter with two split half bridge topology shown in Fig. 14 has low component count but requires large value of capacitors to prevent low frequency current presents in the unbalanced loads [43]. A dual bus inverter with two split half bridge shown in Fig. 15 is also offered for single phase applications due to its modular design and introduces redundancy into the system, but it has more component count [39]. For medium and high power applications, most of the authors give preference to the three-phase PWM converter, because of their simplicity in control techniques. The only drawback is that it has higher component count. Further reduced component counts such as Z source inverter and LLCC resonant inverter are developed for fuel cell applications to reduce the installation cost as shown in Figs. 16 and 17. But it can be used if the electrical isolation is not required [44,45].

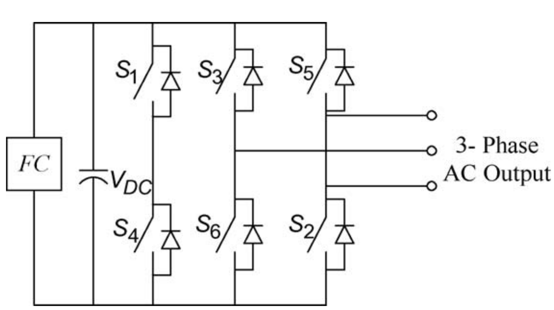

Fig. 15. Single bus three-phase bridge inverter.

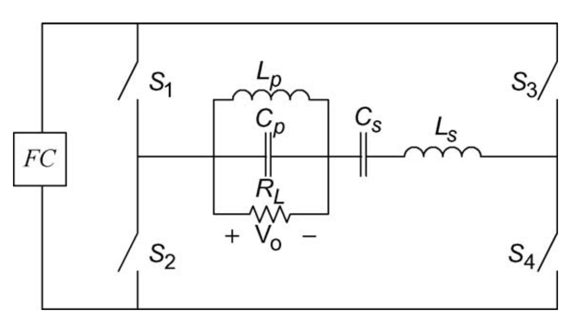

Fig. 17. LLCC resonant inverter.

Table 5
Comparison of different dc/ac inverters.

Topologies	Electrical isolation	η	Advantages	Disadvantages
Single bus inverter with two paralleled half bridge	No	–	Minimum component count	Large dc filter components
Dual bus inverter with two split half bridge single phase 3 wire inverter	No	–	Reliability and flexibility	High component count
	Yes	–	Small passive component	Complex control; for non-isolated circuit, it requires additional passive components
Dual phase inverter with transformer	Yes	–	Boosting capability	Higher cost and size
Three-phase PWM inverter	Yes	~98%	Simple design and control; it requires small value of filter components	–
High frequency link inverter	Yes	~96%	Boosting capability	Highly complex; higher cost and size
Z source inverter	No	~98%	Boosting capability; additional dc/dc converter is not necessary; it saves component cost	Complex control; current stress is high
LLCC resonant inverter	No	95%	Lower current ripples; soft switching techniques	Low power density; it needs large volume and heavy weight of the resonant filter magnetic components

However it can compensate the demerits of conventional inverter topologies and has various merits because of its unique features. All the other dc/dc converter topologies like current fed, series resonant H bridge, voltage doubler, etc. and dc/ac inverters power-conditioning units developed for fuel cell applications are analyzed in this papers [22,46–51]. Moreover the comparison among the different dc/ac inverters based on their types, electrical isolation, operating efficiency and their advantages and disadvantages are given in Table 5.

The research is also focused on multilevel dc/dc converters and dc/ac inverters to increase the power generations for high power applications. Obviously it satisfies the basic requirements, but the only drawback is for each fuel cell stacks at least one switch in working condition that increases the losses, complexity of their control and need of more passive components [52,53].

6. Conclusion

This paper gives a comprehensive review of fuel cell technologies for residential/grid-connected distributed generation system (DGs). The operating principles and chemical reactions involved in different fuel cells and its polarization curve are discussed based on their fuel inputs, electrolyte, advantages, drawbacks and their suitability of applications. The recent developments in fuel cell are analyzed effectively and comparisons of different fuel cells are also made. It is clear from the review that the PEM has high power density, quick start up, lower cost, long life span and almost suitable for all applications. But the MCFC and SOFC are the best choice for medium and large power applications due to their potential of higher efficiency, internal reforming and combined heat and power cogeneration of hybrid systems. In this paper the development of various powers electronic interface devices for dc/dc converter and dc/ac are analyzed effectively and compared. Reduction in cost, increase in the life span more than 40,000 h and development of power-conditioning systems for standalone as well as grid interface are some of the key issues require more concentrated research.

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